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Afterglows of gamma-ray bursts with X-ray features and GRB990705

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Abstract. The absorption feature detected in the prompt X-ray emission of GRB990705 bears important consequences on its circum-burst environment and therefore on its afterglows. Here we investigate whether the circum-burst environment constrained by the absorption feature could be consistent with the observed H-band afterglow, which exhibits an earlier power law decay but a much faster decay one day after the burst. Two kinds of possible sites of the afterglow-emitting regions are suggested: 1) afterglow produced by the impact of the fireball on the surrounding tours that serves as the absorbing material of the X-ray feature; 2)afterglows produced in the dense circum-burst medium inside the tours. In case 1), the faster decay at late time is attributed to the disappearance of the shock due to the counter-pressure in the hot tours illuminated by the burst and afterglow photons. For case 2), the circum-burst medium density are found to be very high ($n \gtrsim 10^4 - 10^5 \mathrm{cm}^{-3}$) if the fireball is a jet or even higher if it is spherical. Future better observations of afterglows of GRBs that have absorption features might give a more definite conclusion to these two scenarios.

Key words. gamma rays: bursts—line: formation—radiation mechanism: nonthermal

1. Introduction

There is increasing observational evidence favoring the existence of absorption and emission lines in the X-ray spectra of Gamma-ray bursts and their afterglows. Emission or absorption features can provide a fundamental tool for studying their close environment (e.g. Mészáros & Rees 1998; Lazzati et al. 1999, 2002; Böttcher & Fryer 2001). To date, five bursts have shown evidence for an iron or lighter element emission lines during the X-ray afterglow (GRB970508, Piro et al. 1998; GRB970828, Yoshida et al. 1999; GRB991216, Piro et al. 2000; GRB000214, Antonelli et al. 2000; GRB011211, Reeves et al. 2002) and one (GRB990705; Amati et al. 2000; hereafter A2000) displays an prominent transient absorption feature at 3.8 KeV during the burst itself.

A few models for emission lines in the X-ray afterglows have been suggested (see Piro 2002 for a review), including "distant reprocessor scenario" and "nearby reprocessor scenario". In the former, the line-emitting gas locates at $R \gtrsim 10^{15}$cm with the line variability time corresponding to the light travel time between GRB and the reprocessor (Lazzati et al. 1999; Piro 2000; Weth et al. 2000). This scenario needs the presence of a iron-rich dense medium with iron mass $M_{\rm Fe} \gtrsim 0.01 M_\odot$. The most straightforward picture is that a SN-like explosion occurs some time before the formation of the GRB. The GRB may be produced by the collapsing of the rotationally-supported newborn massive neutron star to a black hole (Vietri & Stella 1998) or phase transition to a strange star [1] (Wang et al. 2000a) . In the latter scenario, the line emission is attributed to the interaction of a long-lasting relativistic outflow from the central engine with the massive star progenitor stellar envelope at distances $R \lesssim 10^{13}$cm (Mészáros & Rees 2000; Rees & Mészáros 2000).

While different scenarios have been suggested to explain the emission line, the properties of the absorption feature, as in GRB990705, strongly point to a unique scenario, in which 1) the iron-rich absorbing matter of a few solar mass lies between 10^{16} and 10^{18}cm from the burst site; 2) the absorbing matter is located in the line of sight between the observer and the burster.

GRB990705 has a duration of ~ 42 s in the Gamma-Ray Burst Monitor (GRBM) and fluence $(9.3 \pm 0.2) \times 10^{-5} \mathrm{erg\,cm^{-2}}$ in $2 - 700$keV band (A2000). During the prompt phase, it shows an absorption feature at 3.8 keV

[1] Strange quark matter is conjectured to be more stable than hadronic matter (Witten 1984). Farhi & Jaffe (1984) computed the zero temperature thermodynamics of strange matter and found that it may indeed be stable if the parameters of the MIT bag model take values inside a wide "stability wind" they found. Strange stars, composed of this kind of quark matter, may exist and could be born from a massive neutron star as it spins down (Wang et al. 2000a)

and an equivalent hydrogen column density, which disappeared 13 s after the burst onset (A2000). This absorption feature was explained by A2000 as being due to an edge produced by neutral iron redshifted to 3.8 ± 0.3keV with the corresponding redshift being 0.86 ± 0.17. Optical spectroscopy of the host galaxy gives a redshift $z = 0.8435$ (Andersen et al. 2002, in preparation), consistent with the inferred value from the X-ray feature. This straightforward interpretation was, however, questioned by Lazzati et al. (2001) as it requires a vast amount of iron in the close vicinity of the burster. They further suggested an alternative scenario in which the feature is produced by resonant scattering from hydrogen-like iron broadened by a range of outflow velocities. In this scenario, the radius of the SN shell is fixed by the requirement that the heating timescale of the electrons in the absorbing matter is $\sim 10\,$s, i.e. $R_s \sim (2-3) \times 10^{16}$cm.

A fading X-ray afterglow of GRB990705 was detected by the Narrow Field Instruments of *BeppsSAX* 11 hours after the trigger, but the statistics are not sufficient to draw a detailed conclusion on the decaying law (A2000). Masetti et al. (2000) report the detection of the counterpart of this burst twice in the near-infrared H band and only once in the optical V band, from a few hours to ~ 1 day after the GRB trigger. The first two H-band measurements define a power-law decay with index $\alpha = 1.68 \pm 0.10$ ($F \propto t^{-\alpha}$), but a third attempt to detect the source gave an upper limit, implying a much faster decay. No radio afterglow was detected (Subrahmanyan et al. 1999; Hurley et al. 1999).

For the afterglows with X-ray *emission* lines, the line-emitting gas could lie outside of the line of sight of the burst and therefore has no direct relation with the afterglow radiation. However, for afterglow with x-ray *absorption* feature, the absorbing matter (SN shell) should has direct consequence on the afterglow radiation, due to that it must lie in the line of sight of the burst. So, an examination on the self-consistency between the power-law afterglow and the X-ray absorption feature is quite necessary[2].

2. Afterglow models for GRB990705

We here investigate the afterglow behavior of GRBs under the supranova-like scenario where a thick tours of matter (i.e. the supernova remnant shell)lies, in the line of sight of the burst, at a radius R_s from the burst center with a width ΔR_s and particle density n_s, and attempt to give a fit of the H band afterglow of GRB990705, as a represent case. For uniform circum-burst medium, the GRB fireball will be decelerated at a radius

$$R_d = 6 \times 10^{16}\,\mathrm{cm} E_{53}^{1/3} n_0^{1/3} \eta_{300}^{-2/3} \quad (1)$$

where $E = 10^{53} E_{53}$erg is the fireball isotropic kinetic energy, $n = 10^0 \mathrm{cm}^{-3}$ is the particle density of the circum-burst medium, and $\eta = 300\eta_{300}$ is the initial Lorentz factor of the fireball. According to $R_d \gg R_s$ or $R_d \ll R_s$, there are two kinds of possible sites of the afterglow-emitting regions: one is in the tours on which the fireball impacts (case I) and the other is in the circum-burst medium inside the tours (case II).

2.1. case I: jet-tours interaction model

We assume that the tours has a width ΔR_s, density $n_s = M/4\pi R^2 m_p$ and scattering optical depth $\tau_T = \sigma_T n \Delta R_s$. $\tau_T \lesssim 1$ must be satisfied to maintain the flickering behavior of the burst. Values consistent with this could be a few solar mass located at $R_s \sim (2-3) \times 10^{16}$cm, which gives $\tau_T = 0.67 (M/10 M_\odot)(R_s/3 \times 10^{16}\mathrm{cm})^{-2}$ and a particle density $n_s = 10^9 (M/10M_\odot)(R_s/3 \times 10^{16}\mathrm{cm})^{-2}(\Delta R_s/10^{15}\mathrm{cm})^{-1}$.

The tours will be hit by the the fireball shell a few seconds ($\delta t \sim R_s/2\eta^2 c = 2\,s R_{s,16} \eta_{300}^{-2}$, where $R_s = 10^{16} R_{s,16}$cm) after it being reached by the burst proper. The picture of the impact process has been described in Vietri et al. (1999), where the authors attempt to interpret the anomalous X-ray afterglow of GRB970508 and GRB970828. The impact of the fireball on the tours will generate a forward shock propagating into the tours, and a reverse one moving into the fireball shell. They predicted, upon the impacting, a secondary burst from the reverse shock and a very short-lived forward shock. However, we will show below that this forward shock could last few days, giving rise to an early power-law fading afterglow as seen in GRB990705. The disappearance of this forward shock may just account for the observed faster decline at late time.

The forward shock will be slowed down to non-relativistic speeds, after propagating a quite short distance d in the tours, with

$$d = \frac{E}{4\pi R_s^2 n_s m_p c^2} = 5 \times 10^{12} \mathrm{cm} E_{53} n_{s,10}^{-1} R_{s,16}^{-2}, \quad (2)$$

and the corresponding time

$$t_{nr} = \frac{d}{c} = 160\,\mathrm{s}\, E_{53} n_{s,10}^{-1} R_{s,16}^{-2}. \quad (3)$$

For an adibatic shock, the conservation of energy writes

$$E = 4\pi R_s^2 x n_s m_p v^2/2 = \mathrm{constant} \quad (4)$$

where x is the distance that the forward shock have propagated *in the tours* and v is the shock velocity. From this equation and $t \sim x/v$, we get the scaling laws of the dynamic quantities: $v = c(x/d)^{-1/2}$, $v = c(t/t_{nr})^{-1/3}$ and $x = d(t/t_{nr})^{2/3}$. Please note that this dynamic relations are different from the usual Sedov-von Neumann-Taylor solution of a non-relativistic GRB shock (Wijers, Rees & Mészáros 1997; Dai & Lu 1999; Wang et al. 2000b) owing to that here the fireball is decelerated in a dense shell with an almost fixed radius R_s.

As the fireball slows down, the ram pressure of the shell ($P = \rho_b v^2$ where $\rho_b = E/\eta c^2 4\pi R_s^2 m_p x_b$ is the shell

[2] Recently, Ballantyne et al. (2002) studied the self-consistency between the Fe Kα emission line and the X-ray afterglow of GRB991216.

density) on the external tours matter decreases with time. The materials in the tours is supposed to be brought up to a temperature $T_s \sim 10^7 - 10^8 K$ by heating/cooling from the proper burst and its afterglow (Vietri et al. 1999; Paerels et al. 2000). Thus, at a certain distance x_b , the strong counter-pressure ($\sim n_s k T_s$) in the pre-shock tours will finally halt the forward shock. Equating $\rho_b v^2$ with $n_s k T_s$ gives

$$\begin{aligned} x_b &\simeq (\tfrac{Ed}{8\pi\eta R_s^2 n_s k T_s})^{1/2} \\ &= 2\times10^{14}\mathrm{cm} E_{53} R_{s,16}^{-2} \eta_{300}^{-1/2} n_{s,10}^{-1} T_{s,7}^{-1/2}. \end{aligned} \quad (5)$$

The shock velocity at x_b is

$$v_b = c(x_b/d)^{1/2} = 0.16c\,\eta_{300}^{1/4} T_{s,7}^{1/4}. \quad (6)$$

So, the characteristic time when the forward shock vanishes is

$$t_b \sim x_b/v_b = 4\times10^4\,\mathrm{s}\, E_{53} R_{s,16}^{-2} \eta_{300}^{-3/4} n_{s,10}^{-1} T_{s,7}^{-3/4} \quad (7)$$

after the burst.

Up to now, we have assumed that the radial time scale of the fireball shell is relevant to the dynamic time scale. In fact, this requires that the angular spreading timescale does not dominate the radial time scale, i.e. $R_s\theta_j^2/2c \lesssim x/v$, where θ_j is the opening angle of the fireball shell, which means that actually the fireball is a jet. The first measurement of the H-band afterglow is at ~ 4 hours after the burst, so $\theta_j \lesssim 0.3 R_{s,16}^{-1/2}$. Actually, a mildly collimated fireball is quite plausible in consideration of the large isotropic gamma-ray energy of this burst. Please note that, in the jet-tours model, sideways expansion of the jet in the tours can not change the opening angle significantly as the sideways expansion length is much smaller than the radius R_s, i.e. $\theta_j = \theta_0 + c_s t/(R_s + vt) \simeq \theta_0$, where c_s is the sound velocity in the tours.

It is interesting to note that the distance that the shell travelled in the tours before the shock vanishes is comparable to the width of the tours ΔR_s. In such a case, two possible reason could provide the explanation why the H-band afterglow of GRB990705 presents a much faster decline ~ 1 day after the burst: 1) the shock disappearance as discussed above; 2) the shell propagates out of the tours and into a much lower density medium with a sudden drop (Kumar & Panaitescu 2000).

Now we investigate the fading behavior of the afterglow as the non-relativistic forward shock slows down in the tours. During this phase, the typical electron Lorentz factor is

$$\begin{aligned} \gamma_m &= \epsilon_e \tfrac{(p-2)}{(p-1)} \tfrac{m_p}{m_e} \tfrac{v^2}{2c^2} \\ &= 60\tfrac{(p-2)}{(p-1)} \epsilon_{e,0.5} E_{53}^{2/3} n_{s,10}^{-2/3} R_{s,10}^{-4/3} t_{1h}^{-2/3}, \end{aligned} \quad (8)$$

where $\epsilon_e \equiv 0.5\epsilon_{e,0.5}$ is the fraction of the shock energy carried by the electrons and t_{1h} is the observing time in units of one hour. And, the post-shock magnetic field strength is

$$\begin{aligned} B &= \sqrt{8\pi\epsilon_B(4n_s m_p v^2/2)} \\ &= 100\,\mathrm{G}\, \epsilon_{B,-4}^{1/2} n_{s,10}^{1/6} E_{53}^{1/3} R_{s,16}^{-2/3} t_{1h}^{-1/3}, \end{aligned} \quad (9)$$

where $\epsilon_B \equiv 10^{-4}\epsilon_{B,-4}$ is the fraction of the shock energy carried by the magnetic field. Thus we obtain the synchrotron peak frequency

$$\begin{aligned} \nu_m &= \tfrac{\gamma_m^2 q_e B}{2\pi m_e c} \\ &= 10^{12}\,\mathrm{Hz}\,(\tfrac{p-2}{p-1})^2 \epsilon_{e,0.5}^2 \epsilon_{B,-4}^{1/2} E_{53}^{5/3} n_{s,10}^{-7/6} R_{s,16}^{-10/3} t_{1h}^{-5/3} \end{aligned} \quad (10)$$

where q_e is the electron charge, and the cooling frequency

$$\nu_c = 6\times10^{10}\mathrm{Hz}\,\epsilon_{B,-4}^{-3/2} n_{s,10}^{-1/2} E_{53}^{-1} R_{s,16}^2 t_{1h}^{-1}. \quad (11)$$

The peak flux is

$$F_{\nu_m} = \frac{1}{4\pi d_L^2} \frac{q_e^3}{m_e c^2} N_e B \propto t^{1/3}, \quad (12)$$

where $N_e = 4\pi R_s^2 x n_s \theta_j^2/2$ is the total swept-up electrons by the forward shock, θ_j is the opening angle of the jet and d_L is the luminosity distance of the burst. According to these relations, we further derive the spectrum and the light curve:

$$F_\nu = \begin{cases} (\nu/\nu_m)^{-(p-1)/2} F_{\nu_m} & \\ \quad \propto \nu^{-(p-1)/2} t^{-5p/6+7/6} & \text{if } \nu_c > \nu > \nu_m \\ (\nu_c/\nu_m)^{-(p-1)/2} (\nu/\nu_c)^{-p/2} F_{\nu_m} & \\ \quad \propto \nu^{-p/2} t^{-5p/6+2/3} & \text{if } \nu > \nu_c > \nu_m \end{cases}, \quad (13)$$

Thus H-band decay index of GRB990705 before 1 day can be reproduced if $p \simeq 2.8$ and $\nu_H > \nu_c > \nu_m$. In Fig.1, we give an analytic fitting to H-band afterglow. The physical parameters in this fitting are $E = 5\times10^{53}$erg, $R_s = 3\times10^{16}$cm, $n_s = 10^9\mathrm{cm}^{-3}$, $\epsilon_e = 0.5$, $\epsilon_B = 10^{-5}$ and $\theta_j = 0.2$. Under these parameters, the synchrotron self-absorption frequency scales with time as

$$\nu_a = 930\mathrm{GHz}(t/1\,d)^{-(6-5p)/3(p+4)}. \quad (14)$$

Such a large synchrotron self-absorption frequency is consistent with the non-detection of the radio afterglow.

The bremsstrahlung cooling time of the tours of density $n \sim 10^9\mathrm{cm}^{-3}$ is given by

$$t_{br} = 7\times10^5\mathrm{s}\, n_9^{-1} T_{s,7}^{1/2}, \quad (15)$$

so the hot tours does not cool significantly during the phase of the interaction between the jet and the tours.

2.2. Case II: jet in a dense circum-burst medium

The steepness of the light curve decay could be also produced by a usual beamed outflow (e.g. Rhoads 1999; Sari et al. 1999). The beam reduces the energy budget, alleviating the "energy crisis" of GRBs. Assuming that a break due to jet sideways spreading occurs in the H-band light curve of GRB990705 about one day after the burst, the early time slope $\alpha \simeq 1.68$ and the later one $\alpha' > 2.6$ would be consistent with $p \sim 2.9$. The sideways expansion of the jet makes its bulk Lorentz factor Γ slowing down exponentially with radius after a characteristic value θ_j^{-1}. Afterwards, $\Gamma \propto \exp(-r/R_b)$, where R_b is the shock radius at the time $\Gamma = \theta_j^{-1}$. For a uniform circum-burst medium, we have $\Gamma = (17E/1024\pi n m_p c^5 t^3)^{1/8}$ (Sari et al. 1998), and

$$R_b = (\frac{17E_0}{8\pi n m_p c^2})^{1/3} = 7\times10^{17}\mathrm{cm}\,E_{0,51}^{1/3} n_0^{-1/3} \quad (16)$$

where E_0 is the actual energy of the jet, $E_0 = E_{\rm iso}\theta_j^2/2$. If the one-day-long power-law decaying afterglow is assumed to be produced by the deceleration of the jet in the circum-burst medium before it hits the surrounding tours, we requires $R_b < R_s \sim 3\times10^{16}$cm. It immediately means that the circum-burst medium $n \gtrsim 10^4 - 10^5\mathrm{cm}^{-3}$, even if the actual energy of the burst is only $E_0 \sim$ a few $\times 10^{51}$erg as founded by Frail et al. (2001). Frail et al. (2001) have inferred the jet opening angle $\theta_j \simeq 0.054$ from the light curve break time, assuming an interstellar medium of density $n = 0.1\mathrm{cm}^{-3}$. A much larger circum-burst medium density leads to an energy reservoir an order of magnitude larger than what estimated by Frail et al. (2001) as $E_0 \propto \theta_j^2 \propto n^{1/4}$. A much larger density than that of a typical interstellar medium is also suggested by Ghisellini et al. (2002) from the point of view of constraining the total energy reservoir of GRB991216 with emission line luminosity.

Afterglow light curve breaks can also be produced by spherical fireball expansion which undergoes a transition from a relativistic phase to a non-relativistic one (Wijers, Rees & Mészáros 1997; Dai & Lu 1999; Livio & Waxman 2000;). The power-law decay index before and after the break are consistent with $p \sim 3.2$ if H-band frequency locates between the characteristic break frequency and the cooling break one during the first day after the burst (see Eqs.(5) and (6) of Dai & Lu 1999). This scenario also requires that at least the Sedov length of the shock R_{nr} is less than the tours radius. As

$$R_{nr} = (\frac{E_{iso}}{4\pi/3 n m_p c^2})^{1/3} = 2.5\times10^{18}\mathrm{cm}\,E_{iso,53}^{1/3} n_0^{-1/3}, \quad (17)$$

where E_{iso} is the isotropic kinetic energy of burst, it means $n \gtrsim 10^6\mathrm{cm}^{-3}$. Such a large medium density ($n \gtrsim 10^4 - 10^6\mathrm{cm}^{-3}$) is typical of molecular clouds in star forming regions, independently supporting that long GRBs links to massive progenitors.

3. Conclusions and discussions

Emission or absorption features in the X-ray spectrum of GRBs and their afterglows provide a useful tool for studying their close environment and thus their possible progenitors. The absorption feature in the prompt X-ray emission of GRB990705 is originally interpreted by Amati et al. (2000) to be a photoionization K edge of neutral iron. However, this straightforward explanation is shown by Lazzati et al. (2001) to have problems in that it requires a huge amount of iron in the close environment of the burster. Instead, they interpret this as a resonant absorption line broadened by a large spread of velocities. In this scenario, the disappearance of the feature 13 s after the burst results from electron heating due to the illuminating photons and it severely constrains the radius of the absorbing materials ($R \sim 2-3\times10^{16}$cm, see Eq. (13) of Lazzati et al. 2001). A reasonable scenario for this requirement is the supranova-like scenarios (Vietri & Stella 1998; Wang et al. 2000a), in which a young supernova remanent locates at the close vicinity of the burster. Basing on these works, in this paper, we investigated whether the circum-burst environment constrained by the absorption feature could be consistent with the observed afterglows of GRB990705.

We discussed two kinds of possible places of the afterglow-emitting region: one is in the tours where the afterglows are produced by the impact of the fireball jet on this tours and the other is in the dense circum-burst medium inside the tours. In the former scenario, the impact of the fireball on the tours will generate a forward shock propagating into the tours. This forward shock will be decelerated by the dense matter in the tours into a sub-relativistic phase in quite a short time and to a less and less velocity as the time elapse. The heating/cooling processes of the tours by the burst and afterglow photons may lead its temperature to $T_s \sim 10^7$K. Once the ram pressure ($\sim \rho_b v^2$) of the fireball falls to be equal to the thermal counter-pressure ($n_s k T_s$) of the hot tours, the forward shock is halted (Vietri et al. 1999) and the afterglow emission will cuts off accordingly. We found that the H-band afterglow of GRB990705 can be fitted in terms of this model, but the physical parameters in this model can't be well constrained due to the sparse observational data.

In the latter scenario, as many other afterglows, the steeping of light curve decay of GRB990705 one day after the burst is attributed to the jet evolution in a uniform density medium or a spherical fireball undergoing a transition to non-relativistic expansion. The broken power-law decay behavior of the H-band afterglow requires the shock radius at the light curve break time or at the Sedov phase be, respectively, shorter than the tours location. This in turn requires that the circum-burst medium density must be $n \gtrsim 10^4 - 10^5\mathrm{cm}^{-3}$ or $n \gtrsim 10^6\mathrm{cm}^{-3}$, respectively. In this scenario, the fireball will also hit the surrounding tours finally. The abrupt density jump might cause a rise phase and later decline one in the afterglows (see Dai & Lu 2002 for a relativistic case version).

A noticeable point relevant to the high density circum-burst medium is that the true energy revisor of GRB990705 may be much greater than what estimated by Frail et al. (2001), $E_\gamma = 3.9\times10^{50}$erg, derived from the jet model by assuming an interstellar medium of density $n = 0.1\mathrm{cm}^{-3}$, since the calculated fireball true energy depends on θ_j^2 and in turn on $n^{1/4}$.

The sparse data of the afterglow of GRB990705 makes it impossible to give a definite conclusion to the two scenarios. Future better broad-band observations to the afterglows of GRBs that have absorption features may provide more valuable insight of the environment and the central engine.

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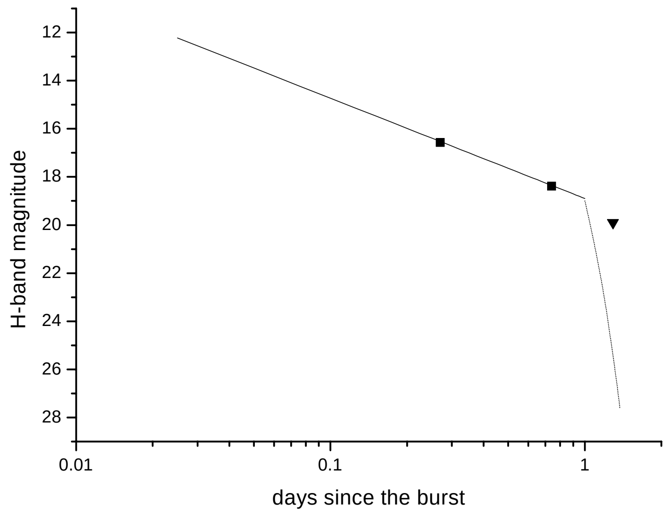

Fig. 1. An analytic fitting of the H-band afterglow of GRB990705 in terms of the jet-tours interaction model (see text for details). Detections and upper limits for the non-detections, taken from Masetti et al. (2000), are indicated by the filled squares and arrows, respectively. The solid line represents the power-law decay of the afterglow as the forward shock slows down and the short-dot line represents the late exponential decay of this shock due to the counter-pressure in the hot tours. See the text for the parameters used in this fitting.